5. DREDGE-AND-FILL ACTIVITIES: SUMMARY AND DISCUSSION

This study sought to quantify dredge-and-fill activities in Galveston Bay as a function of time. The picture that has emerged from the preceding chapters is a bewildering pastiche of detail, depending both on time period and on type of activity, based upon information of highly variable quality. The complexity is a reflection of the range of human activities in which dredging or filling is involved, as well as the complex hydrographic setting of Galveston Bay itself. In this chapter, we attempt to synthesize this information in a more comprehensive form, and to assess the probable impacts of dredging and filling on the Galveston Bay environment. Unlike the previous chapters, in which various data were presented on their own merits and without distortion, in this chapter, synthesis of the data requires assumptions about their nature and hypotheses about operative processes in the bay.

With respect to information quality, quantitative data on federal channel projects is only approximate for the Nineteenth Century, better quantified but only on a project-by-project basis for the period prior to WW II, and capable of yielding space-time variability in some detail only since about 1960. The situation is worse for the non-federal projects regulated by DOA (Section 10/404) permits since WW II, since many permits are non-quantitative, and--worse--there is no record of what permitted work was actually done. The subsample of permit records used for detailed quantitative studies in Section 4.3 above represents about 35% of the dredge-or-fill permits, randomly selected, except excluding projects lying outside of the estuarine sections of the Galveston Bay area, and except for special treatment of the very large permitted projects (which were included only if actually built). According to the NOS data compilation, about this same proportion of 404-permitted projects potentially affecting navigation on the Atlantic Seaboard is actually completed. Therefore, for purposes of this synthesis, we assume that the quantitative data from the 404 subsample applies to the entirety of such activity and is equal to the 404-permitted work actually performed.

5.1 Physiographic alterations

The primary early alterations to Galveston Bay, implemented since the close of the War for Southern Independence, were the jettying of the main inlet and the development of the periphery of the upper bay, especially the Houston area and the region of the Trinity River. These were less important as physiographic alterations to the bay, *per se*, as they were in stimulating shipping on the bay. Stabilization of the inlet resulted in 25-ft controlling depths over the bar, thus affording access to the bay by ocean-going craft. This influx of shipping predictably created a need for trans-bay navigation to the communities on the upper bay, and therefore the development of channels and harbors.

5.1.1 Navigation channels and dredging

At present there are 73 miles of deepdraft (depth greater than 36 ft) channels in the bay, 77 miles of moderate draft (12-15 ft), and well over 65 miles of shallow draft (less than 12 ft) channels throughout the bay. Dredging of navigation channels really began at the turn of the century, at least on a sufficiently large scale to be of concern in this study. The cumulative volume of virgin material excavated from the principal channel systems of Galveston Bay since 1850 is shown in Fig. 5-1. Cumulatively about 260 million cubic yards has been excavated in the creation of this network of channels. By far, the Houston Ship Channel dominates this cumulative volume, as demonstrated by Fig. 5-2, which shows the volume excavated from the two main reaches of this system, the bay reach, transecting the open waters of Galveston Bay (and corresponding to Reaches 1-4 of Table 3-2), and the bayou reach, running from Morgans Point to the Turning Basin (corresponding to Reaches 5-7 of Table 3-2). Together, these account for 80% of the dredged volume, with another 15% accounted for by the Texas City Channel. The GIWW is an order of magnitude smaller in excavated volume than the Houston Ship Channel, and the Chocolate Bayou channel, which is one of the largest private channels in the 404 data base (later incorporated into a federal project, see Table A-4), comprises just over 1%. The total dredged virgin volume, upland and aquatic sites combined, of the 404 projects is 62.9 x 10^6 cu yds, exclusive of Chocolate Bay (but including Texas City Industrial Canal harbor and basin, Bayport Terminal and Barbours Terminal harbor), so in terms of sheer volume on a baywide basis, 404 projects are nonnegligible, but secondary, in comparison to the main navigation channels. It is noteworthy that the 404 data are dominated by several large projects; with these excluded, the others cumulatively are negligible in volume compared to the navigation channels.

Of course, not only is the total volume of the navigation channels of concern, but also their depth and surface area. Table 5-1 summarizes the evolution of channel depths in Galveston Bay over time, giving the project depths for the major channel systems and the year dredging to that depth was completed. The project depths of the Houston Ship Channel system are noted on Fig. 5-1. The cumulative dredged volumes can be compared to the theoretical dredged dimensions of a channel, taking account of the dimensions of the channel *per se* (given as a project depth below the water surface and a bottom width) as well as the sides in which the channel depths slope up to the natural bathymetry. This requires an estimate of natural (i.e., before dredging) water depths. Fig. 5-3 sketches the geometry of the channel cross section relative to natural water depths, from which the "affected" width, i.e., the width of the project at the bay bottom, is computed from

$$w = W + 2\,(D-d)\,a$$

where for simplicity the channel side slope was taken to be 1:2. (Actual side slopes in the Galveston Bay channels range from 1:2 to 1:3.5 in the open bay, and the channels are frequently dredged nearly side-vertical in narrow waterways, especially when the sides are stabilized by bulkheads and dock structures, such as Galveston Channel and the Long Reach of the Houston Ship Channel.) An estimate of channel volume from Fig. 5-3 is $(W+w)(D-d)/2$ times the length of the

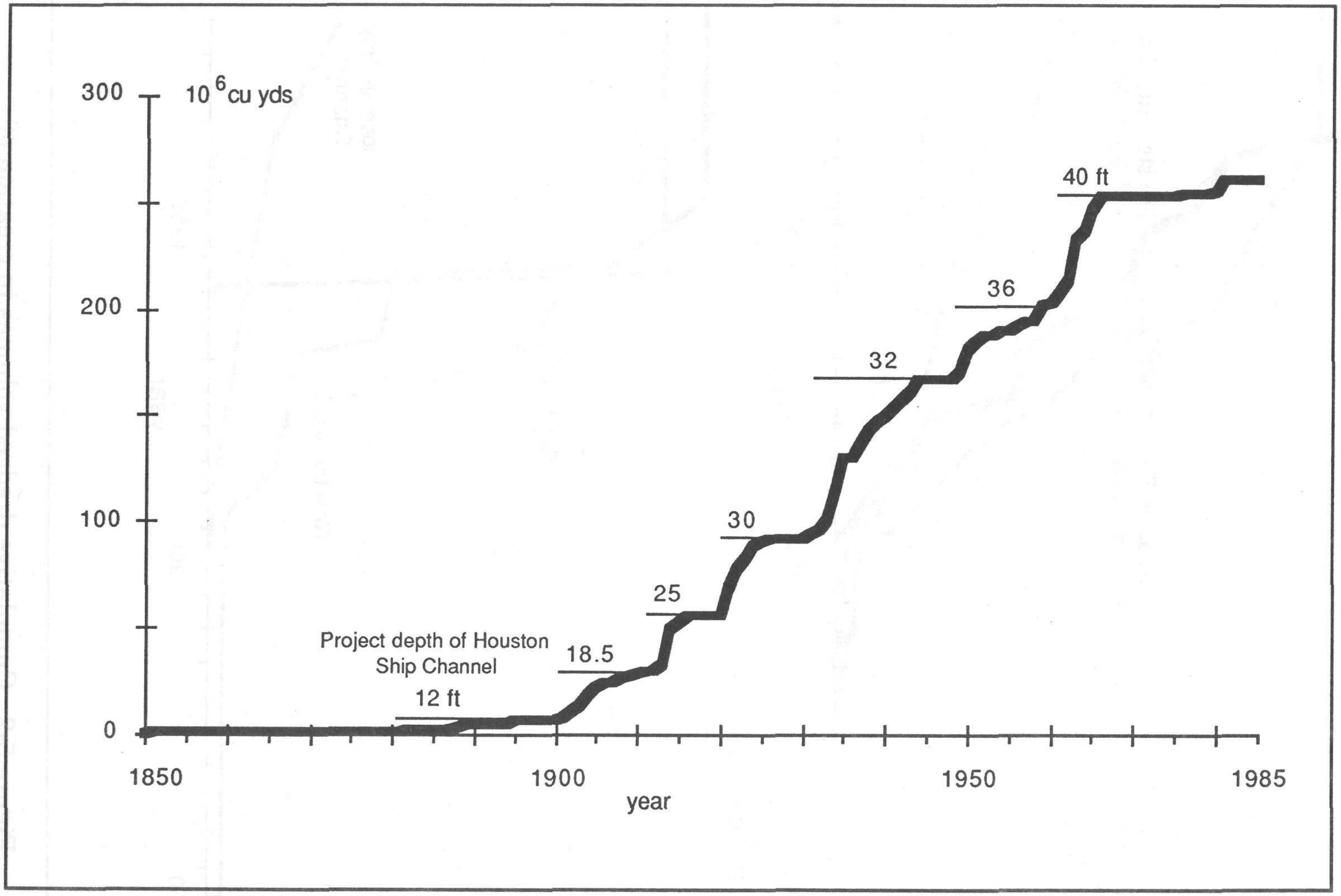

Figure 5-1. Cumulative dredged volume in Galveston Bay navigation channels

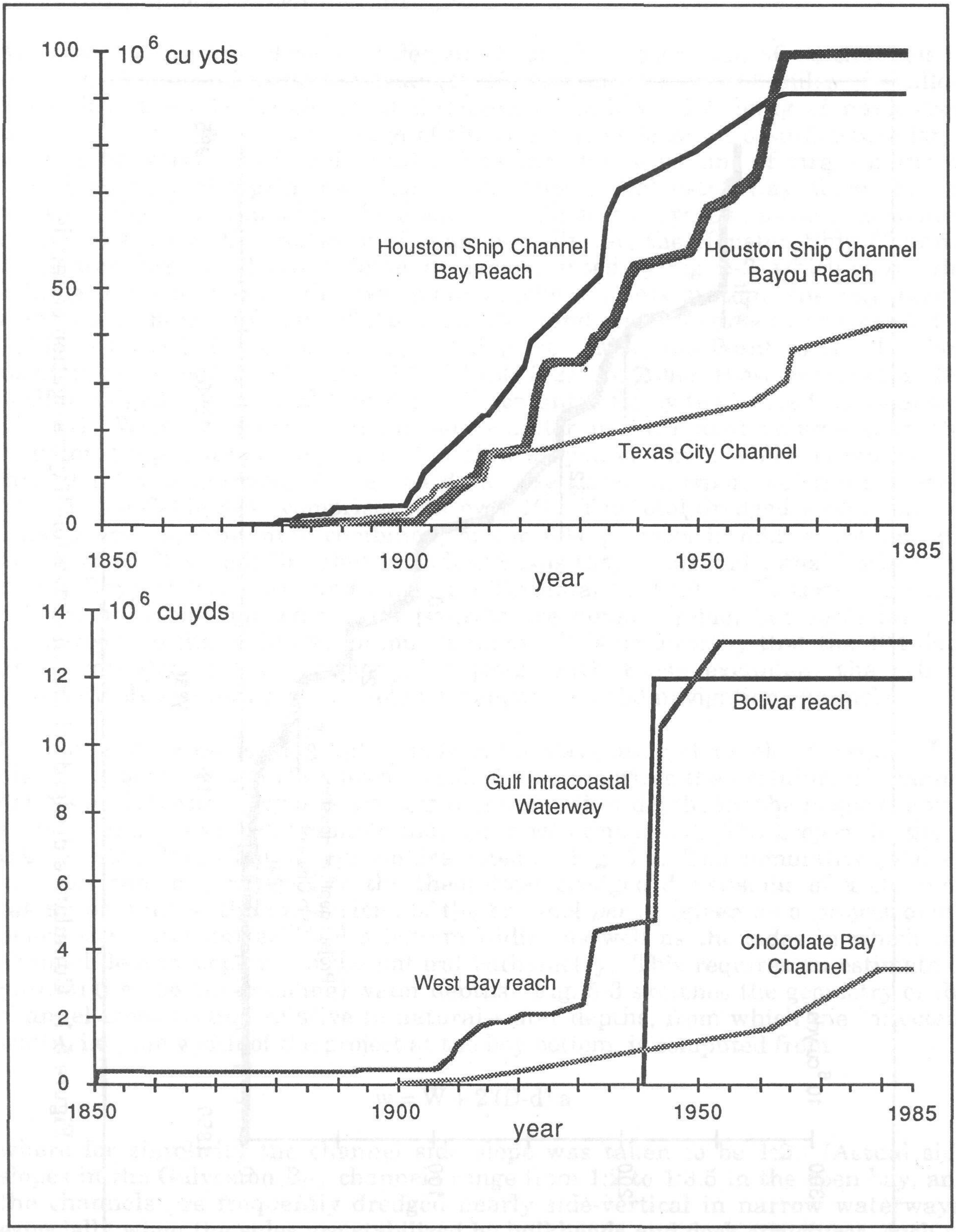

Figure 5-2. Cumulative dredged volumes in creation of principal channels over time

TABLE 5-1

Project depth (feet) for principal channels in Galveston Bay versus date of completion

Date	*Channel project*				
	Houston Ship Channel		Texas City	GIWW	
	Bay	Bayou	Channel	Bolivar	West Bay
1890	12				
1895			16		
1896		12			
1902	17.5				
1905	18.5				
1906			25		
1909		18.5			5
1911			30		
1915	25	25			
1918					6
1922	30				
1924					
1932		30			
1934					9
1937	32		34		
1943				12	
1944					12
1949		32			
1950	36				
1959			36		
1962		36			
1965	40	40			
1966			40		

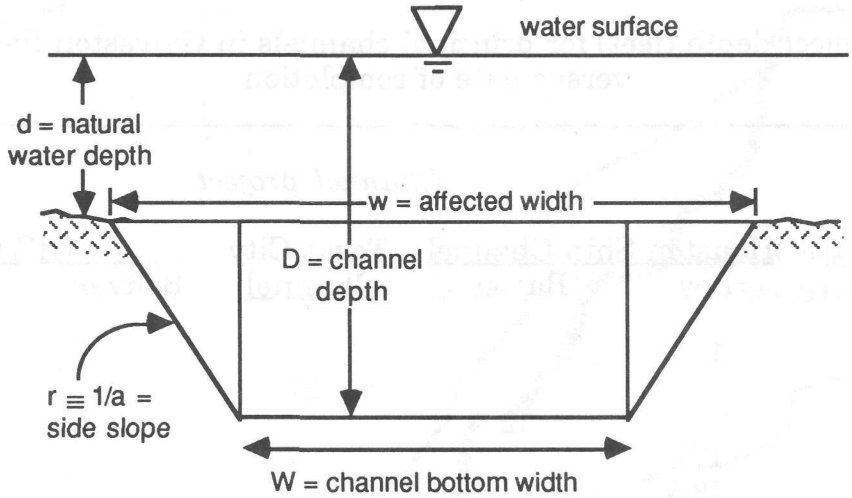

Figure 5-3. Definition sketch for computation of affected width from dimensions of channel.

Table 5-2

Actual cumulative dredged volumes (cu yds) from bay and bayou reaches of Houston Ship Channel, compared to estimate based upon channel dimensions, by year of completion

year	*project*	*cumulative*	*theoretical*
1900	12	4141996	5100000
1909	18.5	18659390	15900000
1915	25	37438320	28000000
1932	30	74918520	67600000
1949	32	127717306	112000000
1962	36	162053630	132500000
1965	40	189688774	153800000

project. For the Houston Ship Channel, the actual cumulative dredging and estimated "theoretical" volumes are summarized in Table 5-2. In general, the dredged volumes systematically exceed the dimension-based estimates, especially after about 1950. This discrepancy is due to the approximations in the volume estimate, especially the constant side slope (which exacerbates the width estimate as the channel becomes deeper) and natural water depths, the practice of overdredging beyond the target dimension to provide "advance maintenance," and, especially in the last four decades, bend-easing, channel rectification, and turning zones.

With the affected widths and the nominal lengths of the channel reaches, the surface area of the dredged channels can be similarly estimated. Table 5-3 summarizes channel areas versus date of completion for the major channel systems. The total area for these channels is about 5050 acres, and, for all of the channel systems of the bay, totals 5910 acres (with the biggest single contribution of the minor channels from the 9 x 150 Channel to Liberty, of 430 acres). Dredging areas for all of the 404 projects (except Chocolate Bayou) total 2980 acres. On an area basis, the 404 projects comprise a much greater proportion of dredging, about one-third, which is a reflection of the proclivity for shallower projects in the 404 sector. Again, there is a domination of the 404 data by a few larger projects.

The total volume of the estuarine portion of Galveston Bay is approximately 3.6×10^9 cu yds (see NOS, 1985). Therefore, the cumulative increment in volume in the dredging projects amounts to about 7% of the bay volume. The total surface area is about 3.4×10^5 acres (NOS, 1985), excluding marshes, of which 2.5% is dredged. (White et al., 1992, give a total estuarine open-water surface area of 4.0×10^5 acres, which is about 20% higher than the NOS value. The NOS number is based upon mean-low-water shorelines current on NOS charts, while White et al., 1992, base theirs on 1989 photogrammetry, taken during low-tide conditions, so on this basis, the two should be comparable.)

5.1.2 Disposal areas

Of the 27,000 acres of disposal area that have been used since WW II within the Galveston Bay system, about half is used for the Houston Ship Channel, 26% for the upper Houston Ship Channel, i.e. the bayou reach, and about 23% for the bay reach. Some disposal areas are no longer active, such as the dike along the Channel to Liberty (9 x 150 project) and a few of the older areas adjacent to the upper Channel. As noted above, the present strategy is to create some sort of confinement for open-water disposal areas, either a levee (or partial levee, such as used on Disposal Area 14-16 along the bay reach of the Houston Ship Channel) or emergent areas of dredged material. Table 5-4 summarizes the disposal areas displacing aquatic habitat. The total area is about 19400 acres, representing 6% of the surface area of Galveston Bay. (The Lost Lake area is somewhat anomalous, in that the aquatic area itself came into existence only recently due to the high subsidence in this area of the San Jacinto River, see Section 5.1.5.) Special note should be made of the status of the open-water disposal areas along the bay reach of the Houston Ship Channel. Most of these, especially those below Red Fish Reef,

TABLE 5-3

Total area (acres) of dredging for principal channels in Galveston Bay

Date	*Channel project*				
	Houston Ship Channel		Texas City	GIWW	
	Bay	Bayou	Channel	Bolivar	West Bay
1890	347				
1895			102		
1896		397			
1902	354				
1905	591				
1906			174		
1909		477			193
1911			231		
1915	675	558			
1918					249
1922	1061				
1924			314		
1932		1085			
1934					498
1937	1569		327		
1943				616	
1944					647
1949		1575			
1950	1620				
1959			334		
1962		1624			
1965	1671	1674			
1966			430		

Table 5-4

Designated and recent (Post-WW II) disposal areas displacing open water, areas in acres, * denotes shallow bay bottom sites

Designation (if available)	*area (acres)*	
HOUSTON SHIP CHANNEL, Bayou Reach		
17	250	Hog Island
18	800	Spillman Island
19	660	Alexander Island
	200*	Black Duck Bay
	825*	Wooster Peninsula & Crystal Lake
20	250	Peggy Lake
21	730	Lost Lake
total	3715	
HOUSTON SHIP CHANNEL, Bay Reach		
1	225	
2	649	
3	347	
4	444	
5	482	
6	64	
7	244	
8	64	
9	64	
10	1106	
11	336	
12	653	
13	69	
14	362	
15	482	
16	546	
total	6387	
TEXAS CITY CHANNEL		
1	1500	Pelican Island
2	296	East of Dike
3	148	
4	89	
5	688	Snake Island
total	2721	

Designation (if available)	*area (acres)*
GIWW (Bolivar reach)	
Rollover Bay	180*
35	141*
38	244*
41	311*
43	600*
total	1476
GIWW (West Bay reach)	
Old Pelican Is.	1000
46-51	771
52	137
53	32
54	44
55	61
56	50*
57	64*
58	25*
59	39*
60	46
61	110*
62	316*
63	549*
67	82*
68	48*
69	22*
total	3396
CHNL TO LIBERTY (9x150)	
Smith	105
Point	150
Dike	350*
Dike	115*
Dike	395*
total	1115

(continued)

Table 5-4

(continued)

Designation (if available)	*area (acres)*	*Designation (if available)*	*area (acres)*
CLEAR LAKE & CLEAR CREEK		CHOCOLATE BAYOU	
1	34	3	10
2	23*	4	15
3	14*	5	21
4	33*	6	8
5	17*	7	12
6	19*	8	23
total	140	9	8
		10	5
		11	7
CEDAR BAYOU CHANNEL		12	8
		13	16
2	58*	14	18
3	55*	15	14
4	62	total	165
total	175		
		DOUBLE BAYOU CHNL	
		1	10
		2	10
ANAHUAC CHANNEL		3	10
14	28*	4	10
15	32*	5	10
16	20*	6	10
17	28*	7	10*
18	48*	8	10*
19	46	9	10*
20	18	10	10*
total	220	total	100

are nonemergent but considerably shoaler than natural depths. While technically these are still aquatic, they are counted as displaced open-water habitat, due both to the altered competency of the sediment and the reserved use for disposal.

Of the DOA (404)-regulated dredging activities, about 90% employ upland disposal, i.e. either in designated, confined disposal areas (notably those created by the Corps of Engineers) or reserved non-aquatic areas, beyond the bounds of the estuarine system. Only 10% use open-bay disposal, and that proportion has been declining. (The Corps advises that the present permitting climate requires upland disposal in almost all cases so this number is approaching 0%.) For practical purposes, disposal areas within the bay of 404-regulated activities are subsumed by the federal designated areas. (Some of the "nonaquatic" areas are within marsh systems, which are discussed separately in Section 5.2.2 below.)

5.1.3 Shell dredging

Following the close of WW II, the expansion of industry in the Galveston Bay area increased the market for reef shell, and shell dredging increased by a factor of 5 or 6. The proportion of Texas shell production from Galveston Bay was on the order of 70%. Numerous cutterhead hydraulic dredges were placed in operation to recover this resource. The principal technological innovation was the use of rotary screens about 1950, by which more of the fines could be retained, and recovery efficiency of the shell improved from as poor as 50% to nominally 90%. The Reef Shell Association, Inc., was formed around 1950 by some of the Texas coast producers, primarily for public-relations purposes. By the mid-1960's, six major operators were permitted for shell dredging in Galveston Bay (Kerr, ca. 1970), including Parker Brothers, Mayo Shell and W.D. Haden (who built the first power shell dredge in the bay in 1905). The trends of annual shell dredging from the entire Texas coast and from Galveston Bay are shown in Fig. 5-4. The annual volume of shell removed from the bay was on the same order as the annual maintenance dredging in all navigation channels.

Shell, however, was a limited resource, and concern increased about the remaining resource during the 1950's. Also as supplies became depleted, direct dredging of, or indirect danger to living reefs (due to siltation) became an increasing problem. In 1953, the TGFOC prohibited dredging within 1500 ft of live reefs, and the following year assigned a warden to monitor dredging. The Shell Survey and Oyster Conservation Association was organized in the early 1950's to be specific to Galveston Bay producers (in contrast to the Reef Shell Association), and sponsored an extensive survey of Galveston Bay for buried shell by J.G. Turney in the period 1954-58. (The only public publication of the results of this extensive survey is apparently the maps reproduced in Rehkemper, 1969.) Approximately 240 x 10^6 cu yds was estimated to remain in the bay, effective 1958, but by the time this number was released in public hearing in 1963, 90 x 10^6 cu yds had been removed (Kerr, ca. 1970).

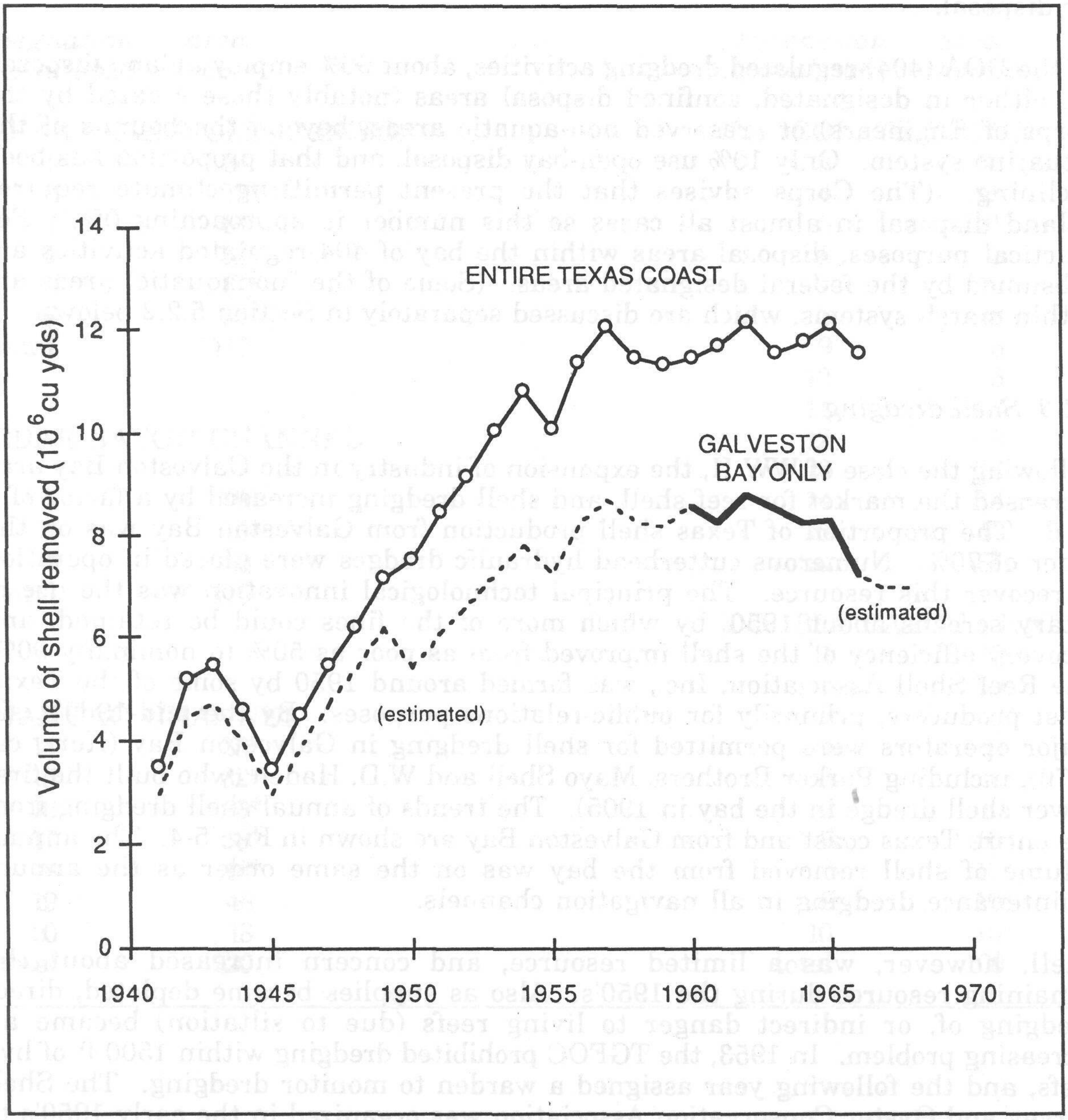

Fig. 5-4. Shell volume removed from Texas coast and from Galveston Bay, post-1940. (Data of Texas Game, Fish & Oyster Commission, compiled by Kerr, ca. 1970.)

By the early 1960's, supply had become the principal problem of the industry. At the same time, the concern about the environmental effects of dredging also increased (Masch and Espey, 1967, Benefield, 1976). In 1963, in response to the dwindling supply, the (newly re-named) Texas Parks and Wildlife Department (TPWD) allowed dredging within 300 ft of live reefs, a considerable reduction from the 1500-ft rule which had been place up to that time. (Tow heads and exposed reefs could also be dredged following transfer of live oysters.) This blanket 300-ft rule immediately produced opposition from environmentalists, so TPWD in 1964 implemented "controlled dredging," involving the close monitoring by TPWD staff. The Corps began to require Section 10 permits as well, requiring the lack of an obstruction to navigation posed by the dredger. Thus shell removal became constrained on the one side by supply and on the other by regulation.

As of 1967, Kerr (ca. 1970) reported that the consensus of producers believed Galveston Bay to contain about 50 x 10^6 cu yds of recoverable (i.e., economically and environmentally minable) shell. However, some producers believed there to be substantially more available in the bay, primarily beneath the principal living reefs in the system. The recoverable volume amounted to a 5- to 10-year supply (depending upon the relative pessimism or optimism of the estimator). Which end of the range was more accurate was effectively mooted in 1969, when shell dredging in Galveston Bay was prohibited. We estimate that cumulatively about 220 x 10^6 cu yds of shell was removed from Galveston Bay from 1910 to 1969. This represents 6% of the aquatic volume of the bay, and is on the same order as the cumulative excavation from the navigation channel network.

5.1.4 Siltation and subsidence

Like all of the broad, shallow bays of Texas, Galveston Bay is normally turbid, with high suspended solids due to the many peripheral sources as well as the scour and resuspension of sediments by both natural agents, such as windwaves and currents, and human agents, such as ships, boats and trawlers. The resulting siltation in channels leads to high maintenance dredging in many areas. Since 1900, a cumulative volume of 650 million cu yds has been dredged from the Galveston Bay channels. The maintenance volumes were expressed as an accumulation per unit area of channel, by using the affected width of each channel system, computed as depicted in Fig. 5-3. These were expressed per unit time by using the period elapsing between dredging contracts. These data are plotted in Figs. 5-5 *et seq.* for different areas of the bay, and the least-squares time-trend line for each is superposed. All of these figures have the same axes, therefore can be intercompared.

These are referred to here as "siltation rates," as indeed they are for the area of the channels themselves. There is a temptation to extrapolate these rates to non-channel areas, and use these as a measure of sediment accumulation on the floor of Galveston Bay. This may or may not be an appropriate extrapolation, depending upon to what extent a channel environment in fact behaves like the open bay, for which we unfortunately lack definitive information. Because a channel is deeper than the surrounding water, it may be subjected to different

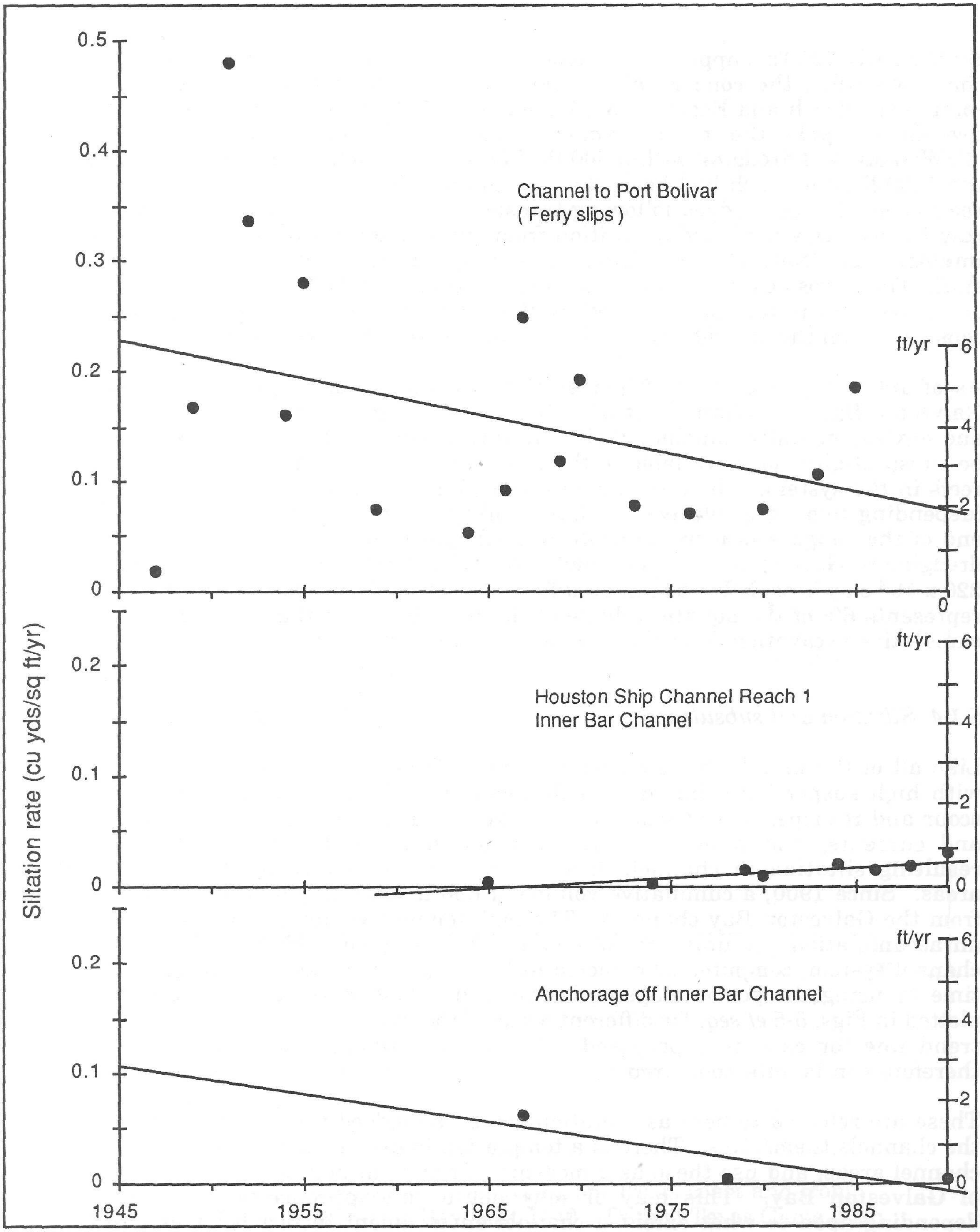

Figure 5-5. Siltation rates in lower Galveston Bay inside main inlet, showing regression lines of trends for 1945-91

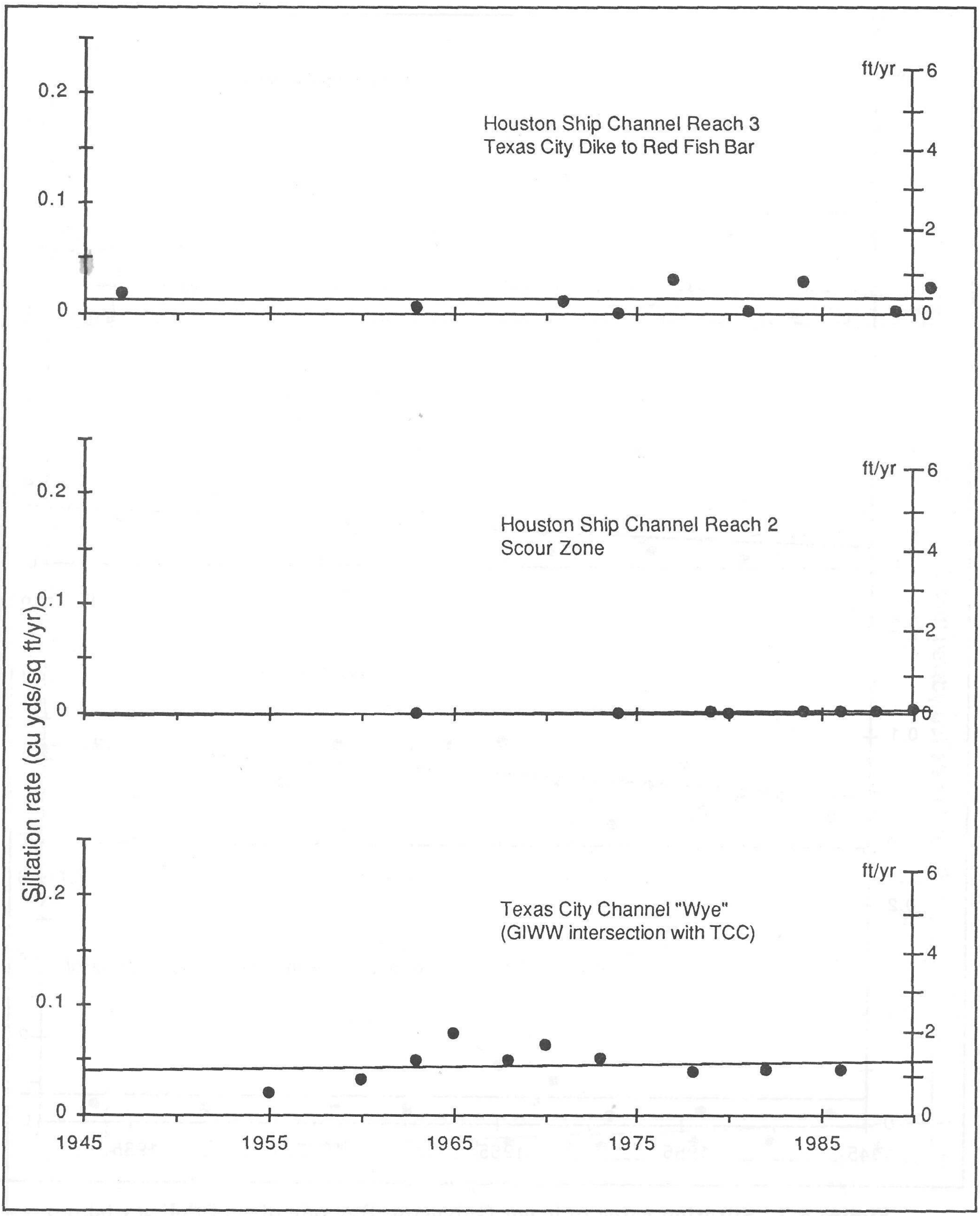

Figure 5-6. Siltation rates in lower Galveston Bay (below Red Fish Bar), showing regression lines of trends for 1945-91

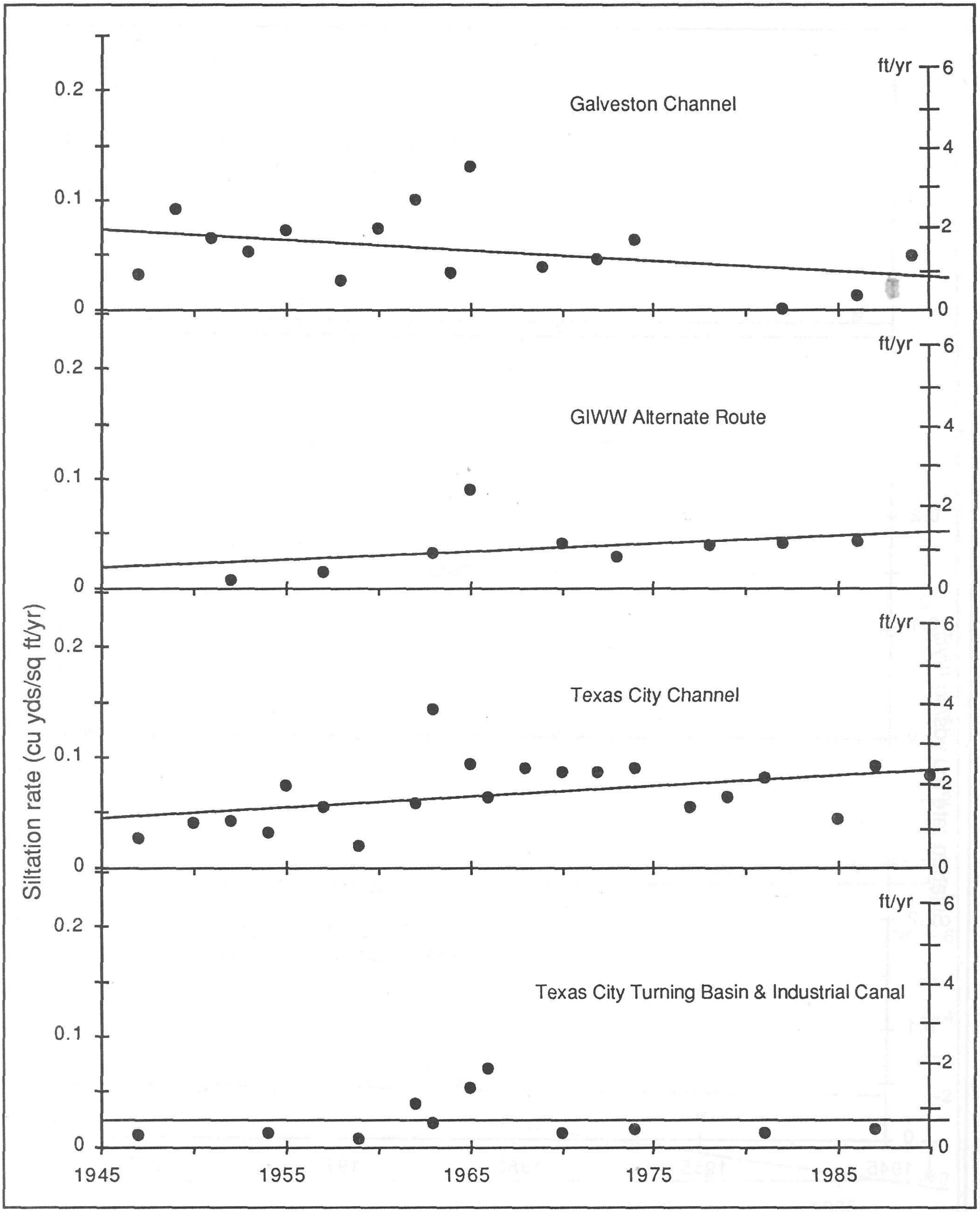

Figure 5-7. Siltation rates in lower Galveston Bay, vicinity of Pelican Island, showing regression lines of trends for 1945-91

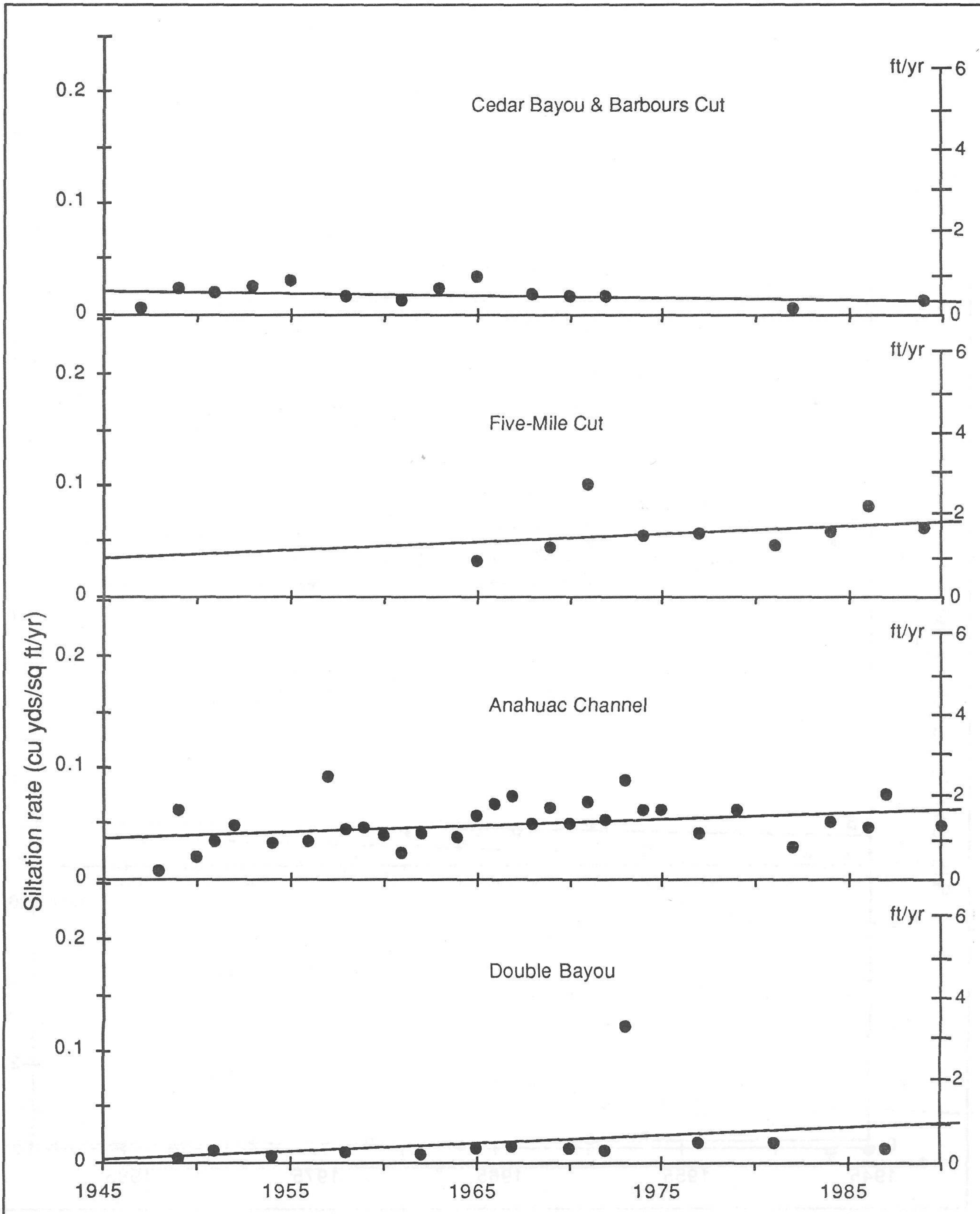

Figure 5-8. Siltation rates in upper Galveston Bay (above Red Fish Bar), eastern segment, showing regression lines of trends for 1945-91

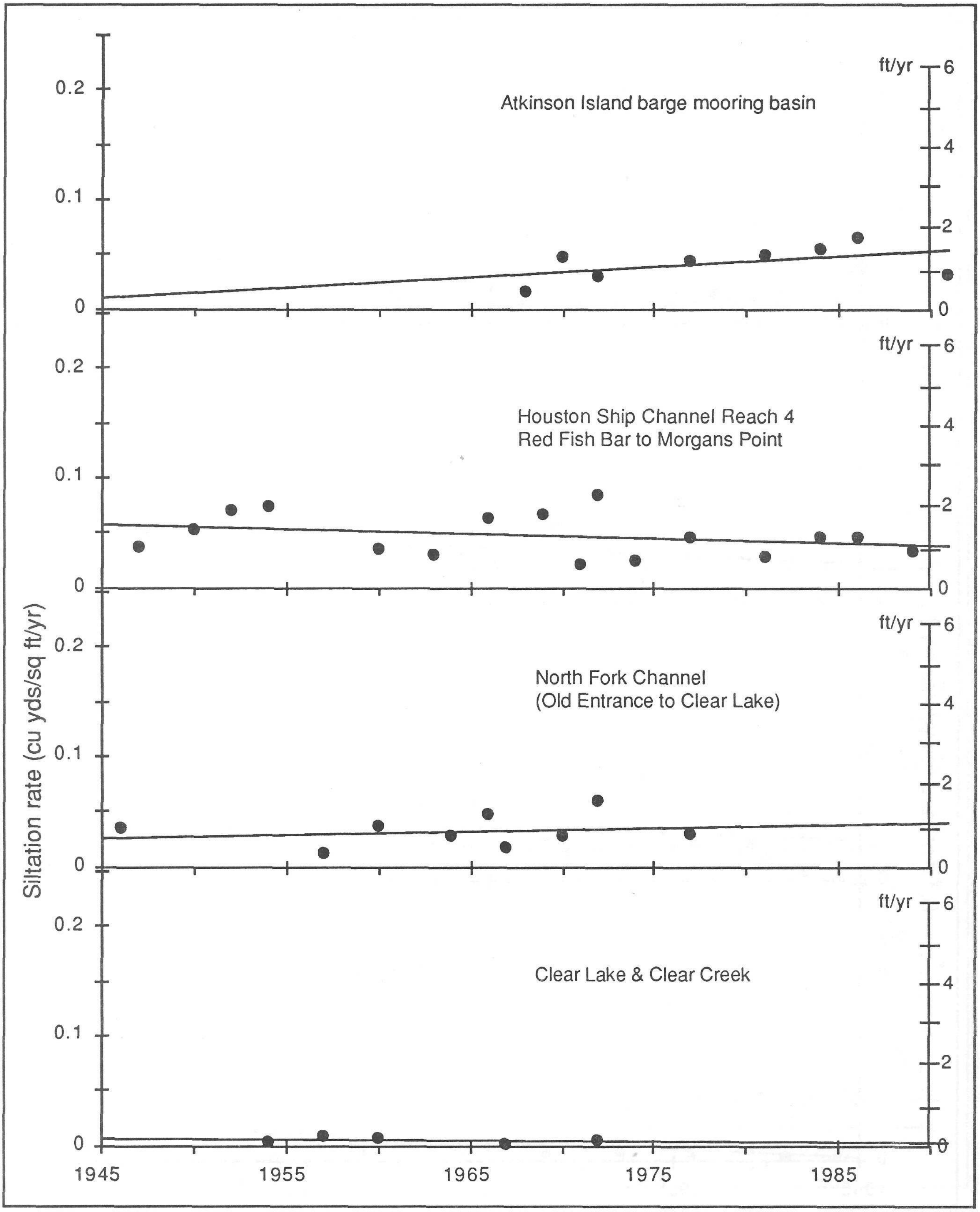

Figure 5-9. Siltation rates in upper Galveston Bay (above Red Fish Bar), western segment, showing regression lines of trends for 1945-91

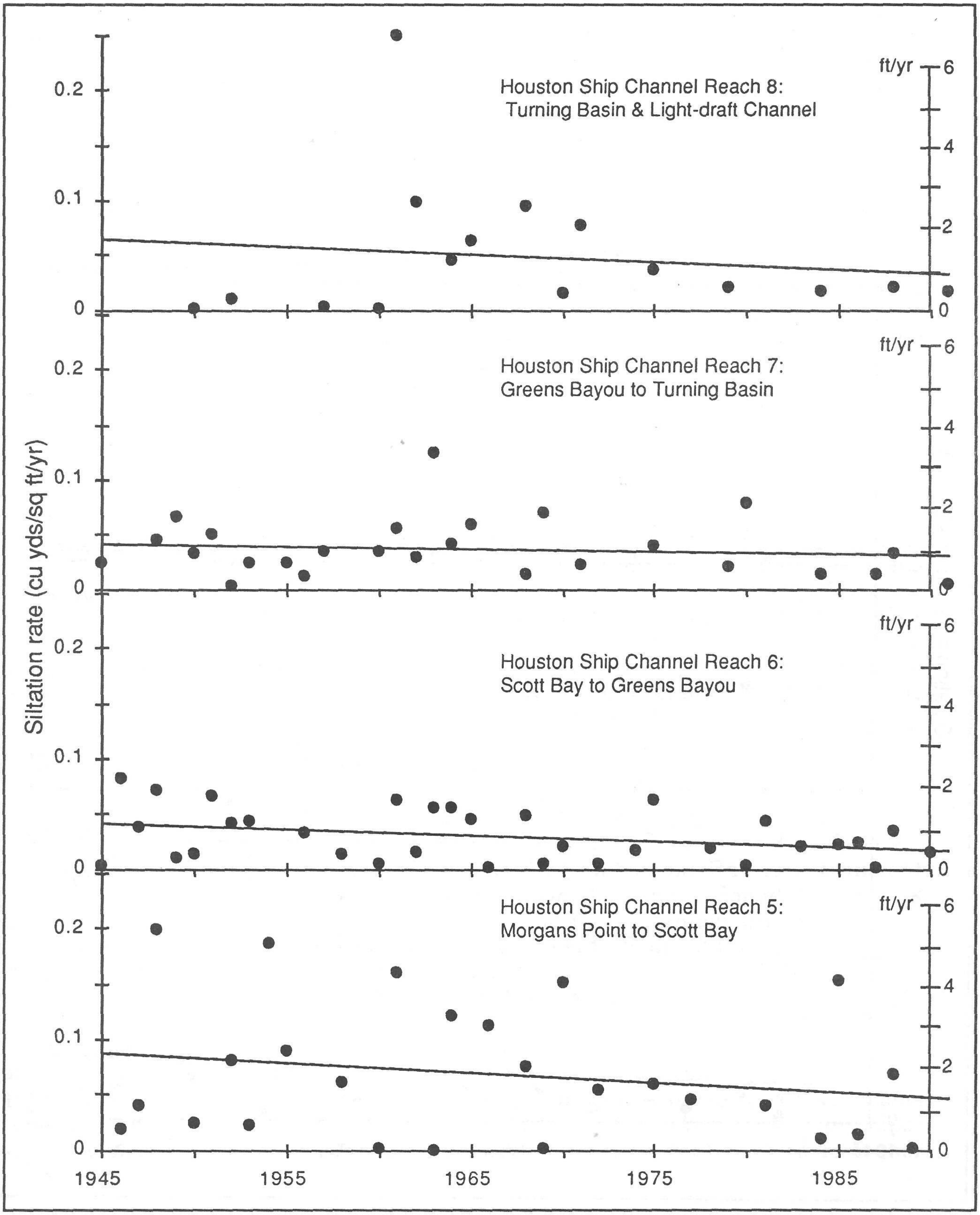

Figure 5-10. Siltation rates in Houston Ship Channel above Morgans Point, showing regression lines of trends for 1945-91

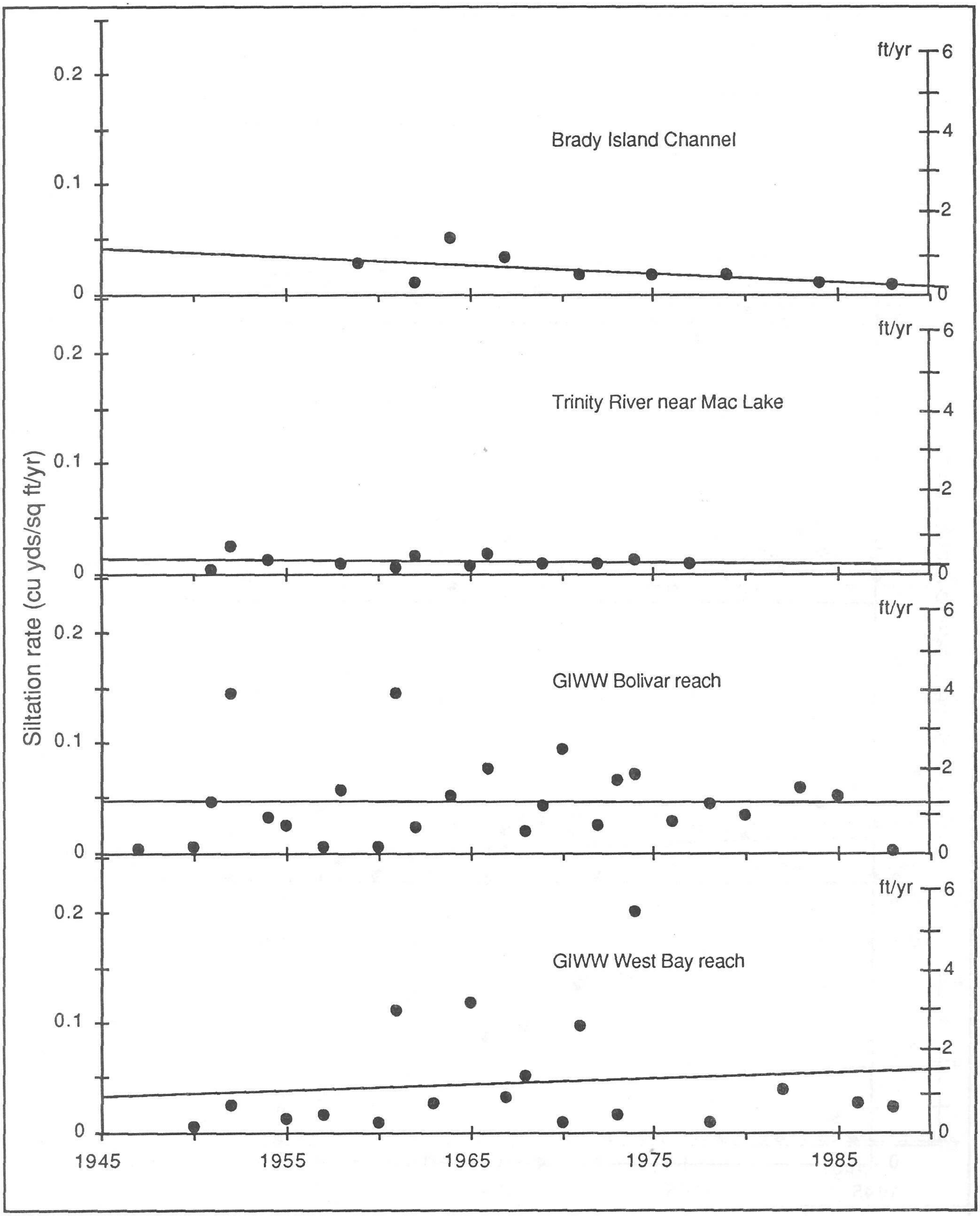

Figure 5-11. Siltation rates in various channel systems, showing regression lines of trends for 1945-91

currents that in turn affect the siltation rates. On the one hand, it may be more sheltered from scour by wave action and from lateral currents, thereby increasing the relative siltation. On the other hand, it may provide a conduit for tidal, meteorological or density currents (e.g., the scour zone of the Houston Ship Channel) and therefore more exposed to scour, with a lower siltation rate. By design, shipping is preferentially restricted to the channels, so these environments are subjected to prop turbulence, wake currents and dynamic displacement of the moving vessel. All of these potentially subject the bed sediments to a complex of hydrodynamics abnormal to the open waters of Galveston Bay.

The highest siltation rates in the system are manifested in the Channel to Port Bolivar, basically the ferry approach on the Bolivar side of the main inlet, Fig. 5-5. This is probably more related to inlet dynamics and interaction with the littoral zone, than to Galveston Bay. (It will be recalled that the harbor channels, those between the jetties, are not considered in this study for that reason.) The lower reaches of the Houston Ship Channel exhibit very low rates, especially Reach 2, referred to above as the "scour zone". Of greatest significance to maintenance dredging is the declining rates in Reaches 4-6 of the Houston Ship Channel, especially since about 1965. Because of the size of this channel, a reduction of the areal siltation rate translates to a considerable reduction in maintenance dredging. In fact, the reduction in overall baywide maintenance dredging since about 1960, see Fig. 5-12 (see also Fig. 3-52), is driven by these reaches of the Houston Ship Channel. Apart from these reaches, and a few others (Five-Mile Cut, Atkinson Island Mooring Basin, the uppermost reach of the Houston Ship Channel, discussed further below), by and large there has been little change in siltation rates in the system since 1945, at least discernible within the noise of the data. Indeed, considering the high variability in maintenance dredging in the bay, an argument could be made that the average rate has been practically constant since about 1920, also demonstrated by the relative constancy of the slope of the cumulative curve of Fig. 3-52. It is noteworthy that, despite the variation in project depth from 25 to 40 ft in this 70-year period, there seems to be no association whatever between maintenance dredging and depth of the channel.

From a longer time perspective, an estuary like Galveston Bay is a transient feature. Initially created by a rise in sea level that outstripped the rate of sediment influx, thereby flooding the Pleistocene river channels and floodplains, the Texas bays have been slowly filling with sediment. Some of the bays with high sediment loads in the rivers have now filled, such as the estuary of the Brazos. The fact that Galveston Bay has experienced net siltation is attested by the numerous buried oyster reefs. By closing a sediment budget, including riverine influxes, shoreline erosion, various accretion zones around the bay, and the activities of man, Gilardi (1942) estimated a net annual accumulation of about 8 x 10^6 cu yds, which would imply an annual shoaling rate of 0.015 ft, for conditions typical of the first half of this century. Of course, in areas near the principal sediment loads, e.g. the mouth of the Trinity, the local rate may be orders higher than the baywide average.

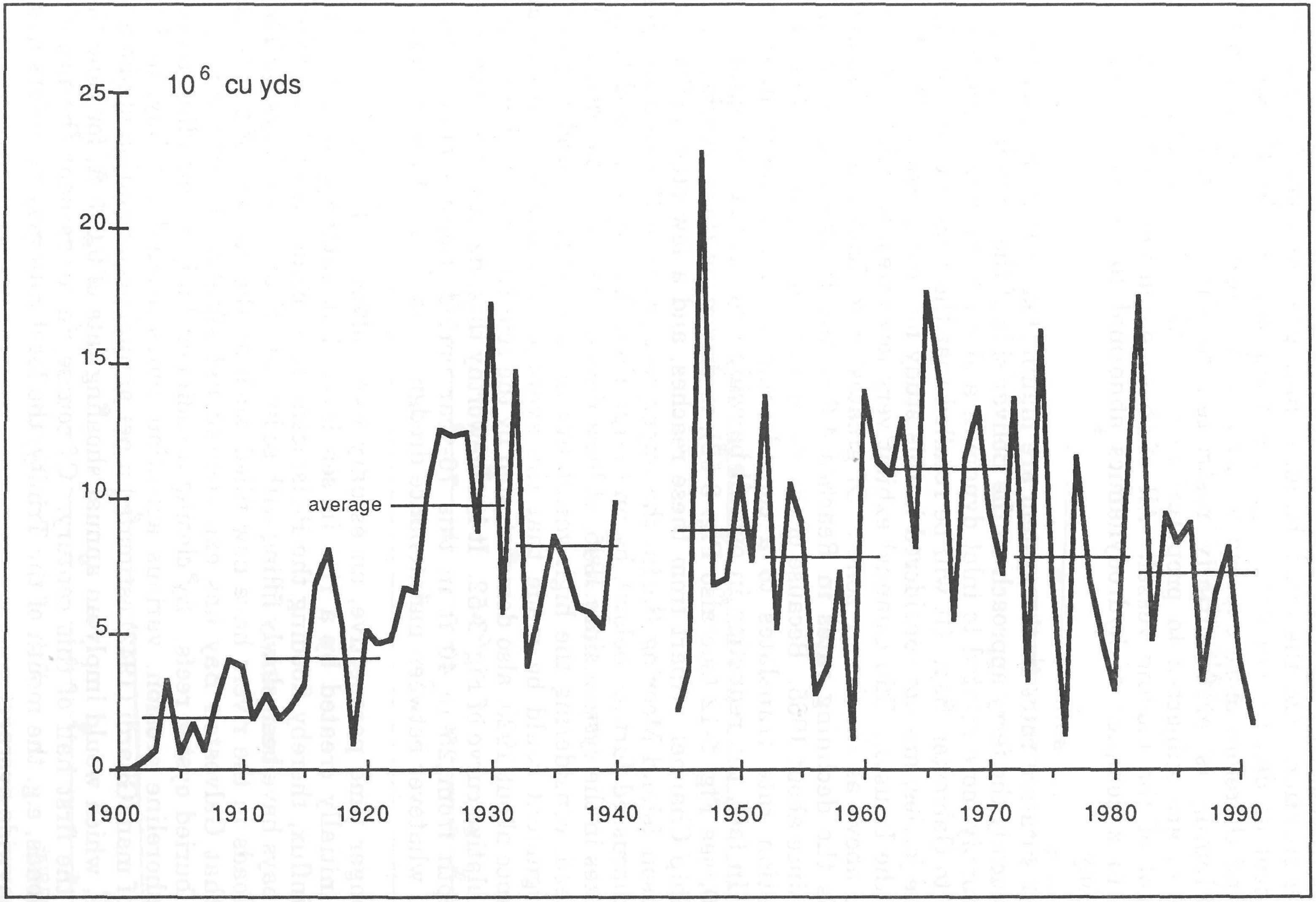

Figure 5-12. Baywide annual maintenance dredging (million cubic yards) since 1900

In this century, Galveston Bay has been subjected to an additional large-scale geological alteration in physiography: subsidence. With its fluvial-dominated sediments, the northwest Gulf of Mexico is gradually subsiding by compaction, but the area of Galveston Bay has experienced accelerated subsidence due to subsurface fluid withdrawal. Data on subsidence in the Galveston Bay area are presented by Gabrysch and Bonnet (1974) and Ratzlaff (1982). In the 75 years since 1900, this subsidence averaged about 1 ft in the open waters of Galveston Bay, and about 7 ft in the bayou reach of the Houston Ship Channel. This has principally been a result of groundwater production from the Gulf Coast Aquifer by the extensive industrial and municipal development of the area, but secondarily a result of oil and gas production (Kreitler, 1977).

The effects of this accelerated subsidence have been dramatic, including the loss of numerous bayshore homes, extensive damage to roads and runways, and activated faulting and stream erosion over about a 5000 km^2 area. The century-old stone jetties at the mouth of Cedar Bayou (see Section 2.1.2) are now totally submerged. Many new areas of watercourse have recently been created by inundation, especially near the San Jacinto River confluence with the Houston Ship Channel. Increased public sensitivity to the problem led to formation of a subsidence district and development of alternative water supplies, and there is recent evidence that subsidence is declining and stabilizing within the region of Galveston Bay *per se* (although not yet in the adjacent upland areas). Monitors operated by the subsidence district indicate about an additional 0.5 ft average subsidence since 1975, ranging up to 1.5 ft on the western shore of the upper bay, and perhaps 2 ft in the upper Houston Ship Channel (HGCSD, 1992).

Using the above-cited data on subsidence (Gabrysch and Bonnet, 1974, HGCSD, 1992), which are net of siltation, the increase in volume of Galveston Bay since 1900 would be about 800 million cu yds, an increase of about 25%. This increase is about three times the total volume dredged from Galveston Bay in all of the navigation channels and 404-regulated permits. Of course, one aspect of dredging, versus subsidence, is that the deepening is concentrated in very local areas of the bay, which can amplify the potential for hydrographic impacts, discussed in the next section.

5.2 Effects of dredge-and-fill activities

5.2.1. Hydrographic effects of dredge-and-fill activities

One of the prime controls on the hydrography of Galveston Bay is its morphology, which constrains the direction and magnitude of currents. It follows that any alteration to the morphology of the bay holds the potential to alter its hydrography, hence the concern with this category of dredge-and-fill impacts. Hydrography and circulation, and related mechanisms such as salinity intrusion, are complex processes, whose analysis is far beyond the scope of this study. For present purposes, we employ judgement, based in turn upon past analyses of field data, and existing studies of hydrography and modeling. Reference is made to the discussions in Gilardi (1942), TDWR (1981), Ward (1980, 1991) and Ward and Armstrong (1992). Many projects, especially those that are small, have essentially local impacts, and will not be given specific discussion. Our primary concern is the larger projects, or those activities implemented over an extended period of time.

Dredge-and-fill activities open the possibility of modifying currents by creating new areas of preferential current movement, due to reduced friction and greater exchange in deeper waters, and by creating barriers to flow. Among the former, probably the most profound alteration to Galveston Bay hydrography was the opening of the main inlet in the last decade of the Nineteenth Century. The construction of the jetties and elimination of the inlet bar structure afforded a much enlarged cross section in Bolivar Roads, and must have had a substantial impact on the tidal prism of the system. It is notable that prior to this, Galveston Channel was evidently one of the primary tidal distributaries in the flood bar, and offered natural depths on the order of 30 ft, requiring no dredging. Since about 1900, when the jetties were essentially complete and 25-ft controlling depth attained in the inlet, maintenance began to be necessary, and has continued to the present. It would appear that the new current trajectories through the inlet were diverted from their historical path through Galveston Channel.

An increased tidal prism would also have impacts throughout the system, not just confined to the inlet, but no quantitative analysis has been performed, and virtually the entirety of extant data holdings on tides and hydrography are post-1900. Tide data were obtained since the mid-Nineteenth Century, but the records now appear to be lost. A computation of tidal prism for the bay was made in 1891 by Galveston District Corps, and determined to range from 120 to 400 million cu yds (for small to great declination). Based upon tide records during the late 1930's, Gilardi (1942) found values 20% higher. But without a careful reconciliation of astronomical parameters and removal of meteorological effects, a direct comparison of these two determinations is probably invalid.

Probably the greatest single project acting as a barrier to flow is the construction of the Texas City Dike, first implemented in 1915 as a 9-km-long timber-pile dike. As noted in Section 2.2.3, this dike was placed directly across the trajectory of Half-Moon current. There is no doubt that it has altered fundamentally the structure of currents in the lower bay, especially during ebb tide and frontal efflux, as indicated in Fig. 5-13. The extreme sinuosity of the ebbing current between the jetties (Gilardi, 1942), whose stagnation zone is responsible for the formation of Big Reef adjacent to the South Jetty, and whose point of impingement has created a prominent scour hole at the base of the North Jetty, is exacerbated by the effect of the dike in focusing flow toward the inlet. A graphic demonstration of the effect of this structure on currents in the bay is given by Fig. 5-14, in which the current streaklines on NASA imagery are made visible by turbidity contrasts. The discharge from the bay is clearly funnelled between the dike and Bolivar Peninsula. Moreover, practically none of this flow enters West Bay north of Pelican Island. (In its late 1930's hydrographic study, the Corps found that some of the flow still "hooked" around the end of the dike into West Bay,

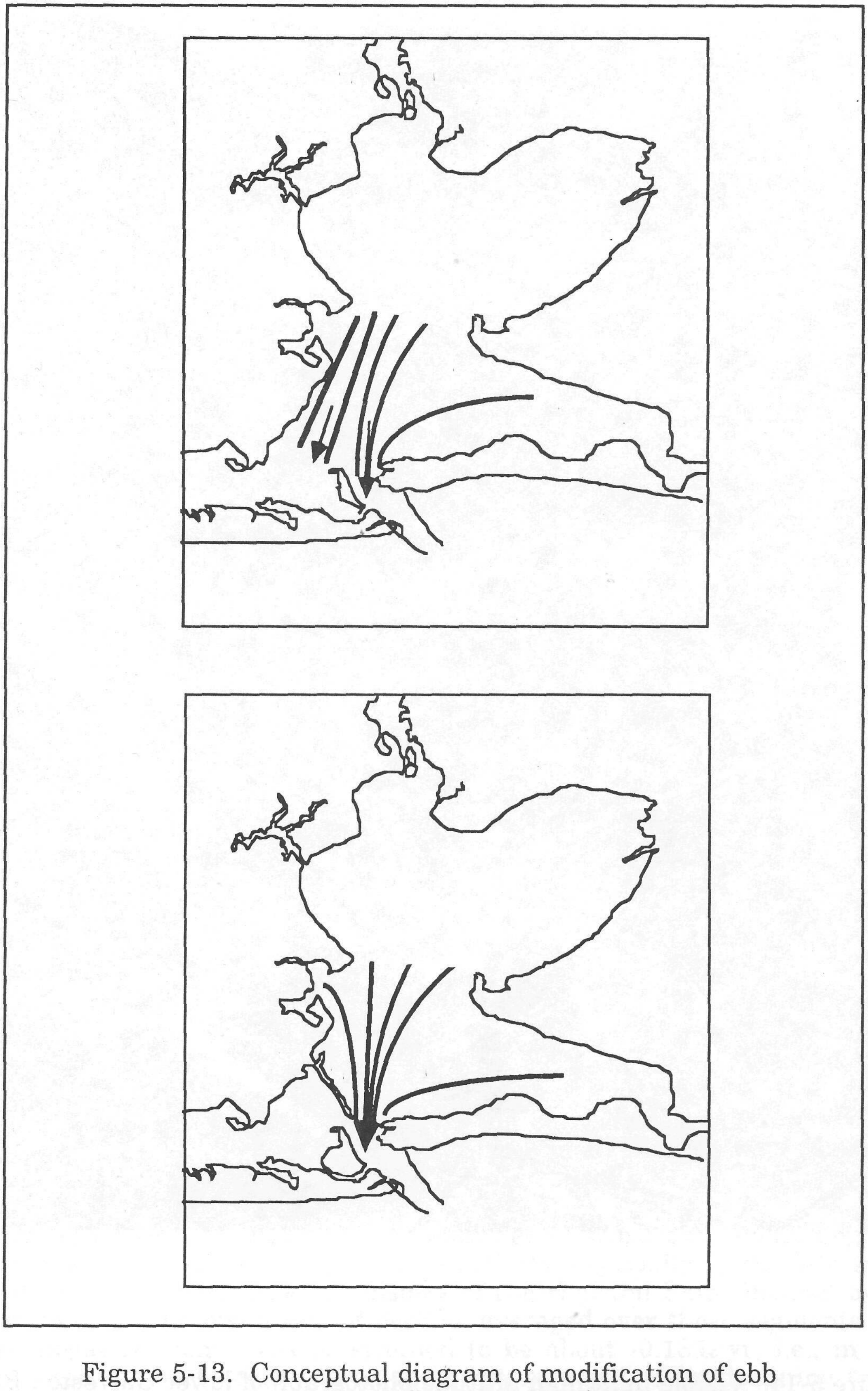

Figure 5-13. Conceptual diagram of modification of ebb currents in Galveston Bay by construction of the Texas City Dike

Figure 5-14. Visible-light high-altitude photograph of lower Galveston Bay during ebb (National Aeronautics and Space Adminstration)

Gilardi, 1942.) Note in this photograph the sinuous current between the jetties and the zone of impingement along the North Jetty.

Another barrier to flow in the system was the dike extending 18 km out across the bay from Morgans Point. First completed as a timber-and-brush dike in 1902, the dike survived for a decade, with high maintenance, until the hurricane of 1911, and allowed stabilization of spoil islands just to the east of the Houston Ship Channel (Atkinson Island). The dike is clearly visible in Fig. 2-3. While the dike is now gone (a few sections of the old dike still survive near Bulkhead Reef), the disposal areas along the channel above Red Fish Reef now serve its original function of blocking lateral flow across the channel. These disposal areas are stable and in many places emergent, and are forming a vast 20-km barrier separating the eastern section of the upper bay (including Trinity Bay) from the western section, see Fig. 3-53.

There are other sections of the bay where dredge disposal areas are becoming sufficiently stabilized so as to act as barriers to flow, notably at the mouth of Chocolate Bay along the GIWW, and east of the causeway, where Pelican Island is by far the most significant. Of course, the dike protecting the Channel to Liberty along the south shore of Trinity Bay is a nearly continuous 28-km barrier to exchange between Trinity Bay and the nearshore waters behind the dike.

One hydrographic impact of great concern is the effect of a deepened ship channel in enhancing salinity intrusion into a bay. The mechanism is the density current, which is greatly amplified by depth, increasing in intensity roughly as the cube of depth (Ward, 1983). While there is a general sentiment that salinity must have increased in Galveston Bay as a consequence of the Houston Ship Channel, based upon experiences with salinity intrusion in other systems, the fact is that such an effect has not been extracted from an analysis of salinity data. This is because of the longevity of the channel. A comprehensive record of salinity in Galveston Bay extends back to about 1950 (Ward and Armstrong, 1992). While this provides over four decades of salinity measurements, the Houston Ship Channel was already at 36 ft in 1950, and has been deepened only 10% since. To extract the effect of such a nominal increase in channel depth in the face of all of the sources of variation in salinity will require analysis of greater sophistication than the usual regression statistics, and may not even be achievable. In one instance on the Texas coast, a deep-draft channel was dredged through a bay without any previous channelization, *viz.* the 36-ft ship channel in Matagorda Bay, dredged in 1963. Pre-channel and post-channel salinities were analyzed by Ward (1983) to determine a systematic increase of about 5 ‰.

It is interesting to note that the data analyses of Ward and Armstrong (1992) disclosed a widespread declining trend in salinity, especially in the late summer values, despite the increasing dimensions of the Houston Ship Channel over the period of record. The mean rate of decline, averaged over those segments with a probable negative trend, was determined to be about -0.18‰/yr, i.e., in a two-decade period, the net decline is on the order of 4 ppt. The declining trend in salinity is most prominent in the lower bay, especially East Bay, and those regions most influenced by intrusion, e.g. the regions west of the Houston Ship Channel.

The most obvious potential cause is, of course, an increase in freshwater inflow. Ward and Armstrong (1992) concluded that, if this is operating, it is too subtle to be discriminated by simple linear statistics, e.g., it may not be so much an alteration in mean inflow as in the time signal of the hydrograph and the response of salinity. Other hypotheses proffered included decreased salinities in the nearshore Gulf of Mexico, decreased interaction with the Gulf of Mexico, altered volume and timing of freshwater inflow events to augment salinity extrusion, and sampling bias in the more recent data.

5.2.2 Habitat effects of dredge-and-fill activities

Dredging and filling potentially affect the quality of the bay environment through modification of water quality, and through replacement of one morphological type (e.g., shallow bay bottom) with another (e.g., emergent island). The principal water quality parameter directly affected by dredging and filling is suspended solids, though there may be indirect impacts on other parameters, e.g. oxygen through resuspension of bottom organics, salinity through modified intrusion in deeper channels, metals, nutrients and organic pesticides through exposure of bed sediments to overlying water, removal of bed sediments to disposal areas, or removal from the water column by adsorption to fine particulates. Salinity was briefly treated in Section 5.2.1 above. The other indirect effects depend upon grain-size partitioning and--more importantly--details of sediment-water interactions in Galveston Bay. Ward and Armstrong (1992) describe the rôle of sediments in suspension and in the bed as quintessential to water quality of the bay, and conclude their analysis of sediment quality with the observation that:

> Every element of the sediment transport process is imperfectly understood, from riverine loads to exchange with the Gulf, from scour and deposition on the estuary bottom to shoreline erosion. The affinity of many key pollutants for particulates, especially metals and pesticides, and the dynamics of transport and exchange within the estuary, render an understanding of sediments absolutely indispensable to the management of water quality in general. ... In our view, sediment dynamics should be the focus of a renewed research effort in the bay, ranging from more detailed observation on grain-size spectrum and its effects, to biokinetic processes operating within the sediment itself.

The same dearth of information delimits what can be said about the effects of dredge-and-fill activities on water quality.

Statistically, there is a clear association between the elevated concentrations of various contaminants, e.g. BOD, various metals, and nitrogen species, and concentrations of dredging activities, both navigation channels and 404-regulated projects, with the largest values of all manifest in the upper Houston Ship Channel. Ward and Armstrong (1992) note elevated concentrations of lead and zinc in the scour region of the lower bay, in both water and sediment, as well as in the regions in which elevated concentrations are expected, such as the Houston

Ship Channel. Unfortunately, all one can conclude from these statistical associations is that there is a statistical association. Considering that the focus of navigation, shipping and industrial wasteloads is also the focus of dredging and 404-regulated activities, an association among all of these is to be anticipated. But this does not allow an inference of cause-and-effect between dredge-and-fill activities and these other factors.

The average distribution of total suspended solids (TSS) in Galveston Bay, by GBNEP hydrographic area is shown in Fig. 5-15. A remarkable feature of TSS in Galveston Bay disclosed by the analyses of Ward and Armstrong (1992) is a declining trend throughout the bay and tributaries. The mean rate of decline, averaged over those segments with a probable negative trend, was determined to be -2.1 ppm/yr, which represents roughly a halving of TSS concentration, from 40 to 20 mg/L, say, in a decade. It is tempting to connect this decline in TSS with the reduction in maintenance dredging taking place over about the same time period. However, the solids in suspension are generally finer than those silting out to the bay bottom and navigation channels, so the association of reduced maintenance dredging with TSS may--at best--indicate a common cause, e.g. reductions in the sources of solids (such as riverine influxes and wasteloads, confined versus nonconfined disposal), driving both bay bottom silting and matter in suspension. We note that the volumetric equivalent of all of the TSS in Galveston Bay is only 100,000-200,000 cu yds, merely 1-2% of the annual maintenance dredging (to say nothing of the other potential sources of suspended matter). Therefore, TSS is probably not controlled by the supply of sediment to the bay, since that exceeds the suspended matter by several orders of magnitude, but rather by the proportion of easily suspended particulates and the mechanisms of resuspension.

Dredging and filling has a much more direct potential impact through the replacement of one morphological type with another, referred to in this study as "habitat." Dredging, in general, replaces the pre-existing habitat with "bay bottom" habitat (referring to the depth of water only). Filling projects and those that create a confined disposal area replace the pre-existing habitat with "upland" habitat, considered to be henceforth isolated, thus removed, from the aquatic estuarine system. The cumulative area dredged in Galveston Bay can be regarded as additional non-shallow bay-bottom habitat, and totals about 9000 acres, federal and non-federal, or about 2.5% of the area of the bay. (Nor does this make any judgment as to the relative quality of this dredged habitat. Clearly, finger canal development with poor circulation in the canals may create bay-bottom habitat that has little ecological value.) On the other hand, about 19,400 acres of bay-bottom habitat have been lost to dredged material disposal areas, about 6% of the bay area. White et al. (1992) compute about 26,000 ac of gain of open-water habitat due to subsidence, about 8% of the bay area.

Table 5-5 summarizes the computed habitat losses from the 404-permit data of this study. (Recall that this data encompasses the post-WW II period with approximately half of the permits issued after 1970, see Fig. 4-1 *et seq.*) Shallow bay bottom (depths less than 5 ft) comprises about 40% of the bay open-water area, some 130,000 acres. The cumulative loss of shallow bay habitat through dredging, both federal and non-federal, totals 1950 acres (1200 due to federal projects), and

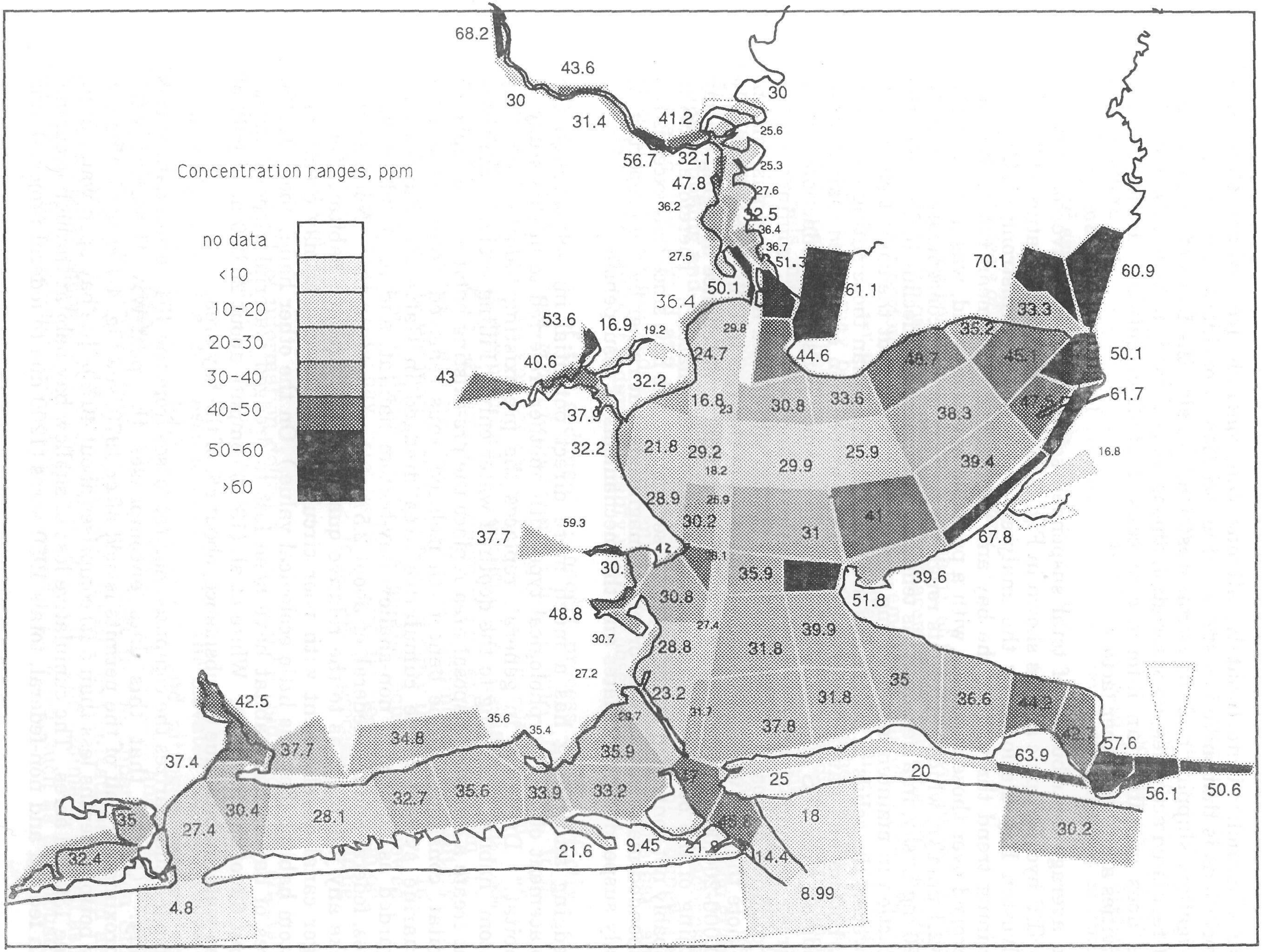

Figure 5-15. Average concentrations of total suspended solids in Galveston Bay, from Ward and Armstrong (1992)

Table 5-5

Habitat alterations due to 404-permitted dredge-and-fill activities (post-WW II)

(a) Habitat losses

	Previously altered	*shallow bay bottom*	*existing dredged area*	*nearshore or shoreline*	*tidal marsh*	*oyster reef*
	replaced by dredged bay bottom:					
number of projects	141	74	127	60	26	2
total area (acres)	773.64	744.28	1906	311.19	461.87	5.79
	replaced by filled upland:					
number of projects	11	19	3	12	22	0
total area (acres)	46.062	99.9	9.01	22.02	2830.7	0

(b) Habitat gains

	Previously altered	*shallow bay bottom*	*existing dredged area*	*nearshore or shoreline*	*tidal marsh*	*oyster reef*
	created by dredging, filling, or mitigation:					
number of projects	0	2	0	0	1	2
total area (acres)	0	1.1	0	0	0.5	85

through disposal totals 6,000 acres, together a loss of about 6% baywide. The effect of subsidence is approximately a loss of 15,000 ac (determined by planimetry) due to deepening of existing shallow-water regions and a gain of about 26,000 ac from submergence of peripheral areas (from White et al., 1992), yielding a net baywide gain of perhaps 11,000 ac, which more than compensates for the loss by dredge-and-fill activities.

Oyster reefs have not been seriously impacted directly by dredging and filling activities (other than shell dredging which has been prohibited in the bay for nearly 25 years). Mitigation of 404-permitted projects has included creation of about 85 acres of oyster reef (subject to the same uncertainty attending other 404 permits, that there is no record of what has actually been implemented).

Dredging, filling and disposal in marshes, totals 7070 acres, of which 2920 acres is due to designated disposal areas (42% of which is in East Bay and 49% in West Bay), 860 acres to navigation channels and 3290 acres to 404-permitted activities. Mitigation has restored or created a negligible amount. As a standard of comparison, White et al. (1992) estimate 1.4×10^5 acres of marsh in the bay system in the 1950's (excluding fresh-water marsh). The dredge-and-fill net loss is about 5% of this. The photogrammetric analyses of White et al. (1992) provide estimates for other categories of gain and loss since the 1950's: losses of 26,500 ac of estuarine wetlands by conversion to open water (principally due to subsidence, secondarily to erosion) and 7,000 ac by conversion to uplands (including dredged material disposal), and gains of 21,000 ac (due to peripheral subsidence and encroachment due to water management in marshes). The net loss given by this photogrammetric analysis is 12,500 ac. (This is relative to a 1950's baseline. The net loss since 1900 would be even greater.) On this scale, the net contribution of dredge-and-fill activities to the loss of estuarine wetlands is over half of the total (assuming, again, a correspondence between this subsample of 404 permits and the 404 work actually performed).

One category of 404-regulated work that appears far more significant to the bay from a habitat point of view than first anticipated is bulkheading. While some bulkheading work requires small amounts of dredging and filling (especially behind the bulkhead), and therefore are included in the quantitative analyses of 404 permits presented above, many do not (or at least indicate no backfilling in the construction plan). Moreover, from both a volume and an area basis, bulkheading is a very minor category of physical works. However, bulkheading (and some related activities, such as revetting and dockworks) represents a direct conversion of shoreline and nearshore habitat from the sloping, rugose, reticulated and vegetated natural state to an abrupt rectilinear barrier. Depending upon how important one views the cumulative fringe habitat of the shoreline and nearshore, this could comprise a habitat impact disproportionate to the actual physical dimensions involved.

Unfortunately, in the detailed examination of the 404 permits, the potential cumulative significance of bulkheading activity was not anticipated, and no measurements were made of bulkheading length. However, a rough estimate of this was made from dimensions of a project. For the 129 404-permitted projects used in the subsample for detailed analysis (*viz.* Pass Two, that we assume in this chapter to approximate the actual 404 projects completed) in which bulkheading was associated with dredging, the bulkhead length was estimated by $\sqrt{(2\pi \cdot \text{area})}$ giving a total of 1.0 x 10^5 ft. (This is the length of a half-circle of the same area. Almost all 404 projects are rectangular and bulkheaded either along one side or along three sides, e.g. a marina. The semicircle geometry is a compromise.) In this subsample, there are 349 dredging projects of which 42% also involve bulkheading. In the entire set of 404 permits for Galveston Bay, the 927 dredging permits are assumed to have the same associated frequency of bulkheading, leaving about 450 permits with bulkheading but no dredging. We assume an average bulkhead length of 800 ft for these, and further assume one-third were actually completed, giving 1.2 x 10^5 ft total length. The total of both sets of bulkheading projects would therefore represent an estimated 2.2 x 10^5 linear ft of bulkheading on the Galveston Bay perimeter.

A logical standard of comparison would be the shoreline length of Galveston Bay. Shoreline length, however, is an indeterminate parameter. It is sensitively dependent upon the scale of resolution: as the scale becomes finer, the measured shoreline length increases. The apparent nonconvergence of this length, and the concomitant indeterminacy of shoreline, were remarked by the visionary British scientist L. F. Richardson, and later by Mandelbrot, for whom the shoreline problem proved pivotal in his study of fractals. Recently, the National Ocean Service undertook a detailed determination of shoreline length of the nation's estuaries utilizing NOS nautical charts and a scale of resolution on the order of 10 m, to resolve such features as service channels, small boat basins, and modified shorelines (Orlando et al., 1988). This is approximately the same scale of resolution implicit in the present project's analysis of 404 activities, and therefore a suitable standard of comparison. The NOS determination of shoreline length of Galveston Bay is 1197 km (which excludes the shorelines of emergent islands and other such offshore features). The above 2.2 x 10^5 ft of bulkheading for 404 projects represents 6% of this length. From direct inspection of NOS charts, the NOS (Orlando et al, 1988) determined 190 km of Galveston Bay shoreline to have been "modified," including bulkheading, revetment, dredged material disposal, piers, groins and related structures. The present study indicates that 404-permitted bulkheading alone accounts for about 35% of this. From the dimensions of designated disposal areas, we compute 80 km of shoreline modified by this activity. That leaves, from the NOS determination, about 45 km of impacted shorelines by docks, revetments, groins, and older (non-permitted) bulkheading. (Unfortunately, the NOS work presented in its 1988 draft report has been abandoned because the shoreline magnitudes were inconsistent with values determined earlier for the same estuaries as part of the National Estuarine Inventory, according to Paul Orlando, pers. comm., 1992. Since the earlier NEI work involved a much coarser scale of resolution, on the order of 1 km, the inconsistency is to be expected. Neither is incorrect; each reflects the scale of resolution employed.)

Finally, in determining these habitat impacts, we have considered the area and volumes of the project work itself. There are several projects in Galveston Bay which have the potential to alter habitat in areas far greater than those associated with the physical displacement of sediment. The jettying and enlargement of the entrance channel noted in Section 5.2.1 above is one such example. Through modified tidal prism and salinity intrusion, this has the potential to have altered profoundly the hydrography of the entire bay. On a much smaller scale, the opening of Rollover Pass in East Bay in the late 1950's exerts some influence on tides, currents, salinities and sediment transport in East Bay. (The Pass was first opened in 1955, closed six months later due to runaway erosion and re-opened in 1959 with flow greatly restricted by a submerged weir, see Bales and Holley, 1985.)

Another class of such projects is those that isolate large segments of the bay or its watershed from direct contact with the estuary. Strictly, analysis of these impacts exceeds the scope of the present study, and would take us far afield into mapping of drainage areas, tidal and atidal inundation zones, and similar considerations. However, the potential impacts of these projects on bay habitat are so great that some mention, albeit qualitative, must be made.

Probably, the most significant of these is the closure of Turtle Bay in 1936. This action eliminated its 6000 acres of open-water shallow-bay habitat and about 10,000 acres of marsh from the estuarine system. For many years, the Delhomme hunting area in the Trinity delta has been operated (now by Methodist Hospital) in which 1100 acres of marsh are enclosed by a levee. (In the last few years, the practice has been to open the area a few times per year for de-watering and exchange with the marsh environment.) Nearby, in the same Trinity Bay marsh, the Houston Lighting and Power cooling pond for its Cedar Bayou steam-electric station isolates (and inundates) over 2500 acres of marsh behind a levee. (This was included in the loss of wetlands presented above since it represents conversion of marsh to open-water.) On the north shore of East Bay, numerous tidal gates, in effect salt water barriers, isolate a significant area of marsh from the system, perhaps 2000 acres. On the west shore of Galveston Bay, the federal Texas City flood control project has leveed the entirety of Moses Lake and Dollar Bay from the rest of the estuary. While there is a 60-ft "tide control gate" allowing some exchange (and small-craft egress), this replaced the natural 2000-ft opening to this tertiary bay, and we can assume a loss to the bay system of its some 1500 acres of shallow-bay and 700 acres of marsh habitat.

These projects, including Turtle Bay, have a total impact on 7,500 acres of bay-bottom and 16,000 acres of marsh. (To this we might add the original Wallisville levee, which would have isolated most of the Trinity delta when completed, but after the project was placed under injunction in 1973, the levee was abandoned and has since breached.) This is 6% of the shallow bay area and 11% of the estuarine marsh of the system.

5.3 Conclusions

Galveston Bay has been subjected to extensive physiographic modification since the turn of the century, some--not all--of which is the result of dredge-and-fill activities. An approximate volumetric accounting of baywide physiographic

Table 5-6

Summary, by volume, of physical modification to Galveston Bay since 1900

Activity	*Volume* 10^6 *cu yds*	*Fraction of Bay per cent*
Deepdraft (>36 ft) channels:	+ 235	+ 6
Other dredging & shallow draft channels:	90	+ 2.5
Dredged material disposal & fill:	- 300	- 8.5
Shell dredging:	+ 220	+ 6
Siltation:	- 500	- 14
Subsidence:	+ 1300	+ 36
Isolation:	- 35	- 1
Net:	+ 1110	+ 30

alterations is given in Table 5-6. Roughly the volume of the bay has been incremented 30% by these activities and processes. It should be noted that of the two largest contributors to this change, we know the least about: siltation and subsidence. Infilling by siltation is estimated at 500 x 10^6 cu yds. The estimated siltation rate of Gilardi (1942), which was based upon a comprehensive, detailed sediment budget for the system, would give a volume of about 700 x 10^6 cu yds from 1900 to the present. However, his data were reflective of conditions in the first 2-3 decades of the century, which may not obtain for the more modern period. Therefore, this estimated volume was reduced to 500 x 10^6 cu yds, to be conservative. The observed subsidence is net of siltation, so gross subsidence was estimated by the net value plus siltation. The large historical contribution of shell dredging should also be noted; this is on the same order as the volume in the network of deepdraft channels.

These figures are cumulative over the bay, and indicate that on a gross volumetric basis the combined *net* contribution of dredging and filling is about 2% of the total physiographic increment in bay volume. The absolute magnitude of material displaced is closer to 30% of the total increment in bay volume, but the majority of this material does not leave the bay system, being placed in the designated disposal areas which displace open water. There are specific regions of the bay in which various types of physiographic change are concentrated, and where the impacts may be locally more significant than one would judge based upon a baywide average. The upper bay and Houston Ship Channel, for example, have exhibited extreme subsidence since 1900, on the order of several feet. The NW-SE midline of the bay, the western periphery, and the SW-NE axis through West Bay

Table 5-7

Summary, by area, of physical modification to Galveston Bay since 1900

Activity	*Area (10^3 acres)* total	*increment to bay*	*Fraction of Bay* per cent
Deepdraft channels:	3.5	0	0
Other dredging & shallow draft channels:	5.4	+ 0.5	0
Dredged material disposal & fill:	19.4	- 19.4	- 6
Shell dredging:	unknown	0	0
Siltation:	unknown	0	0
Subsidence (net of siltation):	26.5*	+ 26.5	+ 8
Isolation:	7.5	- 7.5	- 2
Net:		0.1	0

* from White et al. (1992)

and East Bay, in that order, have the principal concentrations of navigation channel and designated disposal areas.

On an areal basis, the open-water area of the bay has not been significantly changed, as summarized in Table 5-7. This is because the predominant losses due to open-water replacement by fill (primarily disposal areas) and isolation behind barriers has been compensated by new open-water areas created by subsidence. Again, there are areas of concentration of each of these effects, so the baywide numbers do not fairly reflect the extent of physical modification. Generally, the zones of high subsidence do not coincide with areas of disposal. A few exceptions occur along the Houston Ship Channel near the San Jacinto confluence. For example, over half of Duck Bay was lost to disposal during the fifties and early sixties, becoming in effect uplands, but is now reconverting to open-water due to subsidence. Lost Lake was substantially enlarged by subsidence, but is now being filled by disposal.

Maintenance dredging from the entirety of Galveston Bay is dominated by the navigation channels, especially the Houston Ship Channel. Since the turn of the century, about 650 million cu yds has been removed from the channels of the bay. There is considerable year-to-year variability, dictated as much by finances and dredge schedules as siltation. The baywide total has declined about 40% in the last three decades. Most of this decline is driven by the upper reach of the Houston Ship Channel, from above the San Jacinto to a few miles below Morgans Point. While various hypotheses explaining this decline include reduced solids loads from waste discharges, reduced siltation due to better disposal practices, and decreased riverine silt loads from impoundments and altered land use, the most probable cause is simply the great subsidence in this area that has reduced the need for dredging to maintain navigable depths. If a channel has subsided, say, 5 ft, then a great deal more siltation can be accommodated before maintenance dredging becomes necessary.

Projects regulated by 404 permits are highly skewed toward small activities. The 404-permitted dredging activities are more significant on an areal basis than a volumetric (since these projects tend to be shoal draft), comprising about one-third of the total dredged area of the bay. Moreover, these projects tend to be more concentrated in the shoreline, nearshore and shallow-bay areas than the federal projects. The dominant impact of filling is, by far, due to dredged material disposal. Of the open bay area, 6% has been used for disposal, most of which is designated disposal areas used for both federal and non-federal projects.

In terms of habitat impacts, there has been a direct loss of shallow-bay habitat of 1% by area due to dredging and 5% due to filling, principally dredge disposal areas. An additional 1-2% has been lost since WW II due to isolation, i.e. leveeing, impounding or implacement of barriers. (Closure of Turtle Bay, in 1936, represents an additional loss of 5%.) The gain in shallow-bay habitat due to subsidence (net of siltation) is about 8%.

Probably at least 9% of peripheral marshes has been lost to all processes and activities, about one-half of which is due to dredging and filling, primarily dredged material disposal in marsh areas. Another 10% has been isolated from the estuarine system (excluding the inundation by the Cedar Bayou SES cooling pond, which was already counted as a loss of peripheral marsh). No adequate baseline of marsh area at the turn of the century exists; these estimates are relative to a 1950's photogrammetric baseline.

Much of the 404-permitted activities are concentrated in the nearshore or shoreline regions, and therefore may have a disproportionate impact on this fringe habitat. Bulkheading alone is estimated to have impacted at least 6% of the shoreline of the bay. Dock construction and revetment have altered probably another 4%.

In addition to direct impact on habitats, these physiographic modifications are capable of influencing the hydrography and circulation of the bay, and indirectly its water quality. The separation of these type of impacts in the complex hydrodynamic behavior of Galveston Bay is difficult, and little quantitative study has been done. Probable impacts include augmentation of the tidal prism by enlargement of the entrance, construction of deep channels and general deepening of the bay, alteration of internal circulation by barriers such as Texas City Dike and the line of disposal areas along the bay reach of the Houston Ship Channel, and enhanced density currents and salinity intrusion in the deep channels.

5.4 Recommendations

Complete evaluation of the large-scale impacts of physiographic modification to Galveston Bay requires more detailed analysis of the hydrography of the bay than has been carried out in the past. Such hydrographic analysis is also needed to allow a more fundamental understanding of the fluid properties of the bay, most notably its water quality. Yet, despite the recent emphasis on modeling and prediction, many basic aspects of bay hydrography are poorly understood, including sediment dynamics. A comprehensive hydrographic analysis of the bay is recommended, employing historical data on tides, currents, inflows, and water density, as well as modern techniques of fluid-dynamics models and digital data processing. Such a study is long overdue, and will provide valuable information relating to other crucial areas such as wasteload assimilation and biological communities, as well as yielding insight into the hydromechanics of the other bay systems of Texas. (It must be remarked that implementation of a three-dimensional numerical model for the geometry of Galveston Bay and executing a one-year simulation with various channel dimensions does not comprise a hydrographic analysis in the sense used here.)

While this nisus had the prime objective of quantifying dredge-and-fill activities in Galveston Bay, including their impacts on "habitat" categories, no judgment is proffered as to whether these impacts are beneficial or deleterious. Such a judgment must be based upon precisely defined management objectives, which are certainly beyond the present scope. Moreover, an objective evaluation requires closing the connection between hydrography and the biological communities. More attention needs to be given this aspect, including more precise definition of habitats and an evaluation of the effects of each habitat on the biological communities of the bay, as well as other hydrographic interactions, such as water quality and salinity constraints, and recruitment.

A centralized, maintained digital data base on federal dredging activities in Galveston Bay (and the other bays on the coast) would be a great benefit to managers and researchers. Much of the necessary data is now logged digitally at Galveston District, and its routine incorporation into a maintained data base would entail relatively little additional effort. Such a system would also provide a point of contact for transmittal of such information, and would therefore relieve some of the staff burden at Galveston District Corps. Probably, the logical agency to take the lead in implementing such a system is the General Land Office. A similar system for 404-permitted activities is also needed. (See below.)

The greatest uncertainty in the above analysis derives from the inability to quantify DOA (Section 10/404) permit activities. This is a direct consequence of lack of readily accessible data on volume and area of 404 projects, and lack of information on what works are actually implemented under 404 permits. Considering the extensive requirements involved in the 404 process, it is inexplicable that better data are not required as standard entries in the application, and that there is no requirement for self-reporting of activities undertaken within provenance of the permit. The following information is recommended to be required with the permit application, *and* to be filed upon completion of the work or expiration of the permit (the latter should include drawings of the work actually performed):

Volume and area dredged and filled
Length of shoreline to be modified
Latitude/longitude of the project (approximate)
Characteristics of the areas to be dredged and filled
Additional structures or modifications, with dimensions

However, it is not clear to this writer to whom this recommendation is proffered, since it is not within the prerogative of Galveston District Corps and Region VI EPA to impose their own requirements on 404 permitees. The Corps advises that the first three items are now part of present application requirements.

As noted at several points in this report, the Corps regulatory program has evolved significantly over the period represented by the data base of this study. Regulations have changed and staff sizes have grown, especially in response to an increasing environmental awareness. Many of the above suggestions have in fact been recognized and implemented by the Corps, including much more follow-up on permitted activities.

Several agencies involved in the administration or review of Section 10/404 permits have implemented digital data bases to streamline the process, including the Corps of Engineers, Environmental Protection Agency, and National Marine Fisheries Service. However, each of these systems is narrowly focused on the factors of most importance to that agency's operations, mainly administrative schedule points and actions. A more comprehensive digital system should be formulated incorporating all of these administrative elements, but also including quantitative data on the permitted activities, including those listed above. The data formats employed in this study (see Appendix B) might serve as one model for the level of information detail. Clearly, the system should also have provision for accommodating information on work actually performed. As a continuing effort, older permit records should be added to this data base so as to extend the coverage back in time. Implementation of a comprehensive data base system is rather urgent, since as time passes without such a system, current information is being lost whose recovery will require even more effort in the future.